Transport Canada
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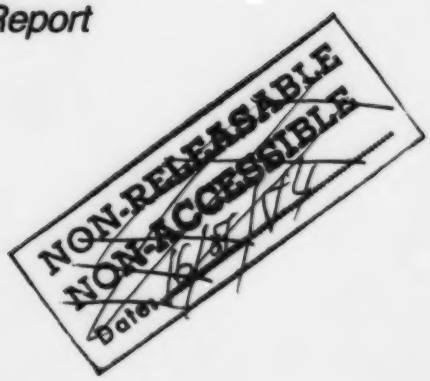
Développement

TP 5168E

M.V. ARCTIC
Propulsive Performance

Summary Report



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M.V. ARCTIC

PROPULSIVE PERFORMANCE

Transportation Development Centre / Centre de développement des transports (GSLA)
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SUMMARY REPORT

For

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DISCLAIMER

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17. Abstract

This report summarised the principal results of a study to evaluate the propulsive performance of the M.V. Arctic when operating in ice. The database was collected between 1979 and 1981 on the ship's special instrumentation system during normal commercial voyages into eastern arctic locations as permitted for a CASPPR ice class 2 vessel. Dedicated ice trials were also conducted at other opportunities to expand the database.

The findings are interpreted with respect to the machinery provisions of Classification and CASPPR. The conclusion is reached that, for this particular vessel, propulsion system and operating data range, there was no significant exceedence of the laid down design criteria. Potential problem areas are identified, however, with recommendations for their treatment in future designs.

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17. Résumé

Ce rapport reprend en les récapitulant les résultats de l'étude faite en vue d'évaluer le comportement du groupe propulseur de l'Arctic lorsque celui-ci navigue dans les glaces. La base de données afférente avait été rassemblée grâce au système de saisie installé à bord, durant les voyages commerciaux réguliers faits de 1979 à 1981 dans la mer Arctique, conformément aux dispositions du Règlement sur la prévention de la pollution des eaux arctiques par les navires, applicables à un navire de cote arcrique 2. En outre, des essais spécialisés avaient été faits dans le but d'enrichir cette base de données.

Les résultats confrontés aux dispositions dudit Règlement et des sociétés de classification montrent que, dans la limite des données acquises, l'Arctic respecte largement les exigences de base concernant la machinerie et la propulsion de cette catégorie de navires; toutefois, certains problèmes existent à l'état latent et des recommendations ont été formulées en vue de les résoudre à l'avenir.

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1.0 INTRODUCTION

This study is one of a series of five complementary studies commissioned by the Transportation Development Centre (TDC) "to improve the fund of knowledge in the public domain concerning the performance of an icebreaking bulk carrier operating in the Arctic". The particular objective of this study is "to determine the effect of ice ingestion on the performance and strength of the main machinery, gear train, shafting and propeller of the M.V. ARCTIC" by the analysis of data recorded in 1979 to 1981 by a Data Acquisition System fitted to the vessel.

The M.V. ARCTIC is a 28,000 DWT bulk carrier built to comply with the requirements of the Canadian Arctic Shipping Pollution Prevention Regulations (CASPPR) for Class 2 vessels. The propulsion system fitted, by choice of the owners, is in excess of that required by the Regulations with respect to power. The power required by the CASPPR for a vessel of the dimensions of M.V. ARCTIC is about 4,200 kW as compared to 11,018 kW which has been installed. The scantlings and strength of the connected systems reflect the increased power of the engine and also the additional strength required by the CASPP Regulations based upon machinery of the installed horsepower. Details of the vessel are shown in Table 1.

The vessel has historically traded between Europe and Nanisivik in Strathcona Sound, Baffin Island and the Polaris Mine, Little Cornwallis Island between 25 June and 15 November each year. This operating window is as allowed by the CASPP Regulations for Class 2 ships for the area in which the terminal ports are located in the Arctic.

The data bank, from which the analysis of the strength and performance of the propulsion system has been carried out, has been recorded during commercial voyages to and from the Canadian Arctic and during dedicated trials of the vessel in the Arctic, Lake Melville, Labrador, and Saguenay River, Quebec, in the period 1979 to 1981.

The ice conditions in which the vessel has operated and data collected include:

- 1.8 m thick level first-year ice and ice ridges in Admiralty Inlet in late June/early July when ramming is necessary;
- thin first-year ice;
- mixed pack ice of first, second and multi-year floes in Baffin Bay and Lancaster Sound in October and early November

The ice conditions experienced during data acquisition, however, do not necessarily represent the maximum ice conditions likely to be experienced in the vessel's permitted operating period in the Arctic.

Length Overall (LOA)	209.55 m
Length Between Perpendiculars (LBP)	196.59 m
Breadth Extreme (B)	22.93 m
Depth Moulded (D)	15.24 m
Draft (Full) (H)	10.93 m
Displacement (Full)	38,104 tonnes
Installed Power	14,770 BHP (Metric) 11,018 KW (S.I.)
a) Main Engine - M.A.N. 52/55A 14 Cylinder 450 r.p.m.	
b) Gearbox - Renk Single reduction, vertical offset, with 3.147 reduction ratio	
Propeller Diameter	5.27 m
a) Lips - Controllable pitch - four blades - single propeller - 143 r.p.m. located in Wageningen 19A nozzle with 25 mm tip clearance	
Bollard Pull at Full Power	160 tonnes
Classification - Lloyd's [✠100A1, Ice Class 1A Super, LMC]	
- Arctic Class 2 (CASPPR)	
Ballast Capacity	28,329 tonnes
Fuel Capacity	1,852 tonnes

TABLE 1

M.V. ARCTIC - PRINCIPAL PARTICULARS

2.0 DATA MEASUREMENT SYSTEM

The recording of the data was in digital form onto magnetic tape by a Data Acquisition System controlled by a Roim 1603A mini computer. The output from the various sensors was recorded after being digitized by an ADC (analogue to digital converter) with a maximum total sampling rate of 1,765 samples/second. The sampling rate most commonly used for dynamic data channels was 10 samples/second and for information channels, e.g., environmental data 1 or 0.1 samples/second. Higher sampling rates have been used on occasions.

A total of 212 data channels were incorporated into the Data Acquisition System of which 173 were for hull structure measurements, 8 propulsion system, 6 auxiliary systems, 15 ship performance and 10 environmental sensors. Of these parameters, the recordings of those shown in Table 2 have been scanned and analyzed.

3.0 DATA SCANNING AND REDUCTION

Due to the large volume of data collected during the 1979-1981 period and the requirement of detailed identification of various ship and ice parameters, the work of the data reduction has been performed with the aid of computers using an integrated computer program package developed for this project.

The tapes have been processed by a CDC Cyber 750 mainframe computer at the Canadian Cybernet Centre, Toronto, and the output transferred through a data communication link to the MSL in-house HP model 9816 computer for subsequent manipulation and analysis. This arrangement combines the benefit of the high efficiency of a mainframe computer and the cost effective and graphics capability of a desk-top computer.

A flow diagram outlining the procedure of data reduction and analysis is depicted in Figure 1.

A two-step approach has been adopted to search and read the data of ice/propeller interaction events from the magnetic tapes. The tape has been scanned quickly by monitoring a selected number of propulsion performance data channels (shaft torque, thrust, r.p.m. and ship Doppler speed log) and the mean, maximum and minimum values of those channel data are extracted at 30 second intervals. Figure 2 shows the variations in torque and thrust obtained from coarsely scanning the tapes at a sampling rate of one sample every 30 seconds of recording time. As can be seen in the figure, several events of large and abrupt changes of shaft torque and thrust are observed. These events provide an overview of the signature of the propeller and ice interaction.

Selected ice events from the first scan have been reread in order to extract the actual record of the event and other related channels for detailed analysis. Figures 3 and 4 show an example of fifteen data propulsion channels obtained from the second reading of the tape.

PARAMETER MEASURED	TYPE OF SENSOR
Shaft Torque	Strain Gauge Bridge
Shaft Thrust	Renk Thrust Meter Type RCIK-3
Propeller Pitch Response	Follow-Up Potentiometer
Fuel Rack Position	Follow-Up Potentiometer
Shaft RPM	Shaft Tachometer
Ship Speed	Sperry Doppler Speed Log
Combinator Setting	Follow-Up Potentiometer
Propeller Pitch OD Box Differential Pressure	Pressure Transducer Selabs Type SE21/V
Rudder Torque	Strain Gauge
Accelerations: Heave, Surge, Sway - Aft	Accelerometers

TABLE 2

PROPULSION SYSTEM SENSORS

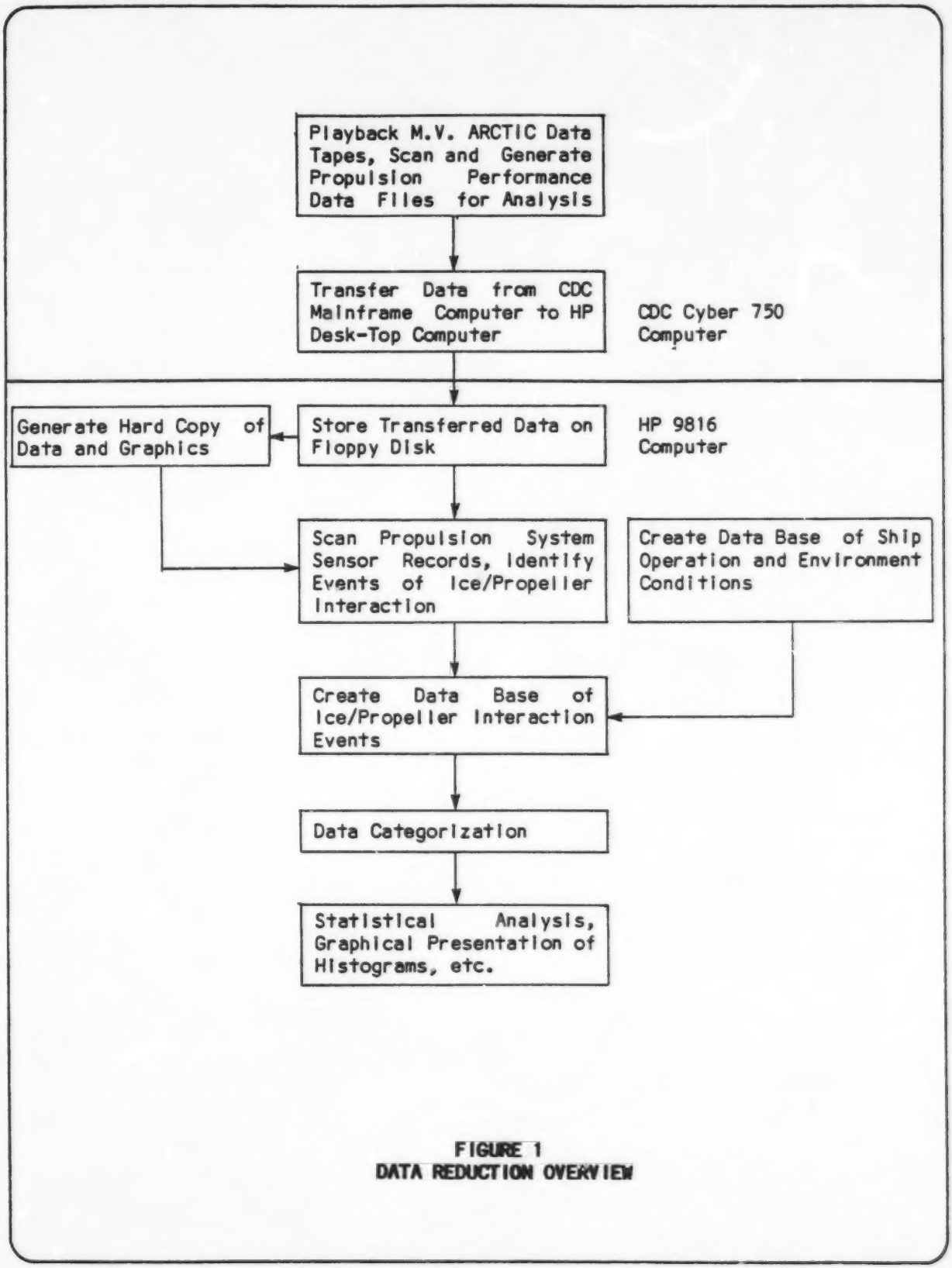
Playback M.V. ARCTIC Data Tapes, Scan and Generate Propulsion Performance Data Files for Analysis
Transfer Data from CDC Mainframe Computer to HP Desk-Top Computer
CDC Cyber 750 Computer
Store Transferred Data on Floppy Disk
Generate Hard Copy of Data and Graphics
HP 9816 Computer
Scan Propulsion System Sensor Records, Identify Events of Ice/Propeller Interaction
Create Data Base of Ship Operation and Environment Conditions
Create Data Base of Ice/Propeller Interaction Events
Data Categorization
Statistical Analysis, Graphical Presentation of Histograms, etc.

FIGURE 1
DATA REDUCTION OVERVIEW

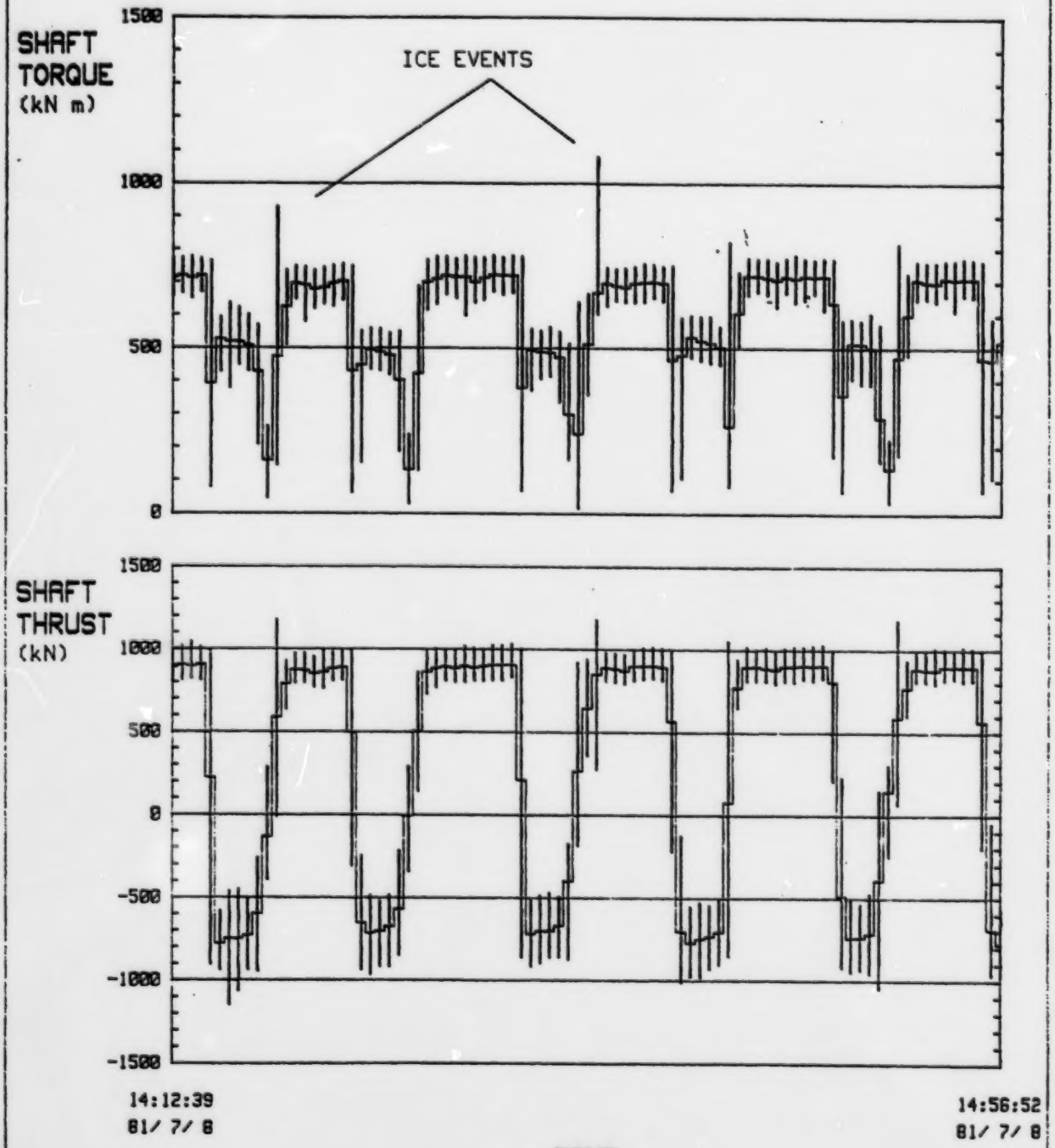

FIG. 2 SAMPLE OUTPUT FROM THE FIRST TAPE SCAN

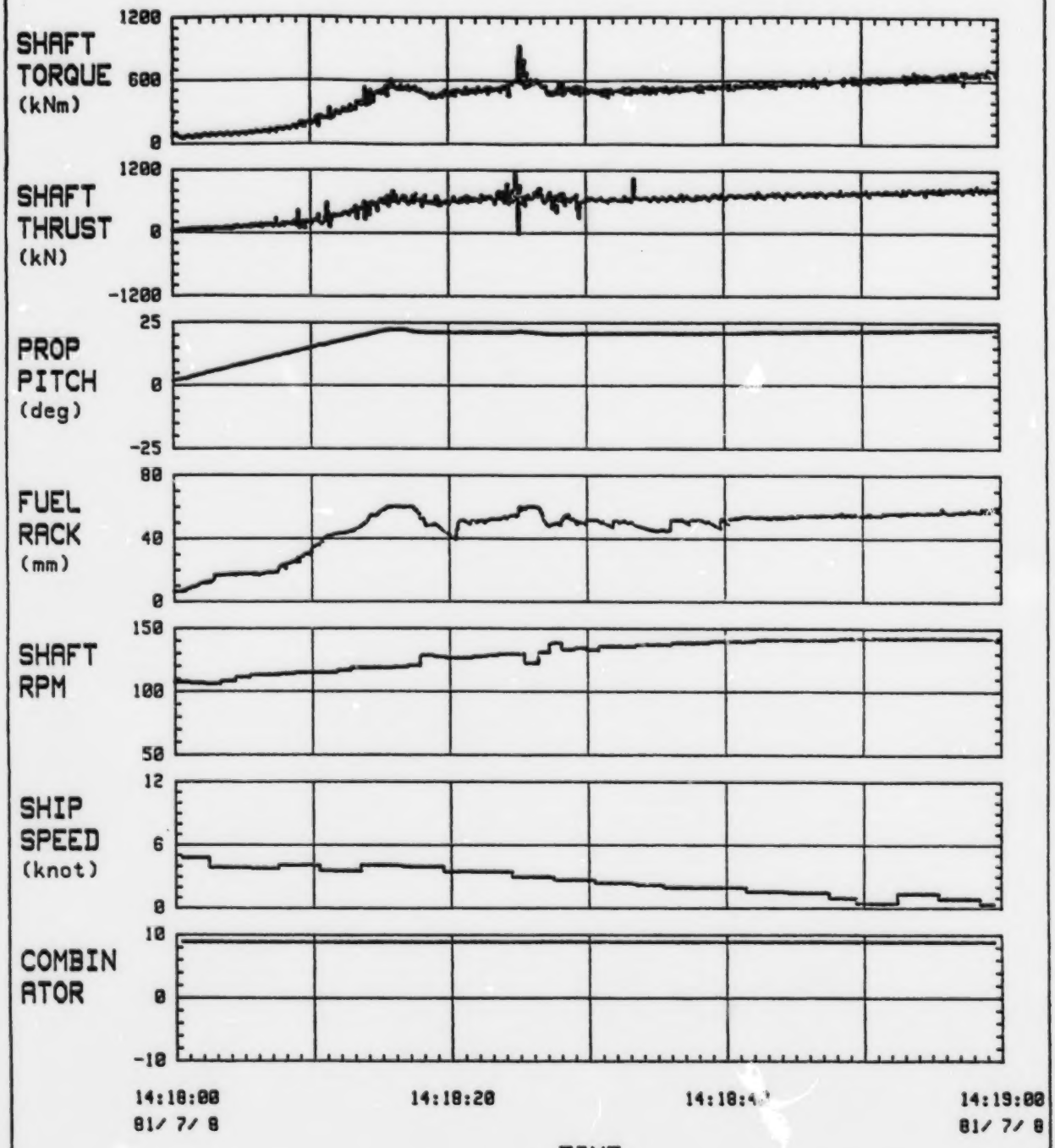

FIG. 3 SAMPLE OUTPUT FROM THE SECOND TAPE SCAN

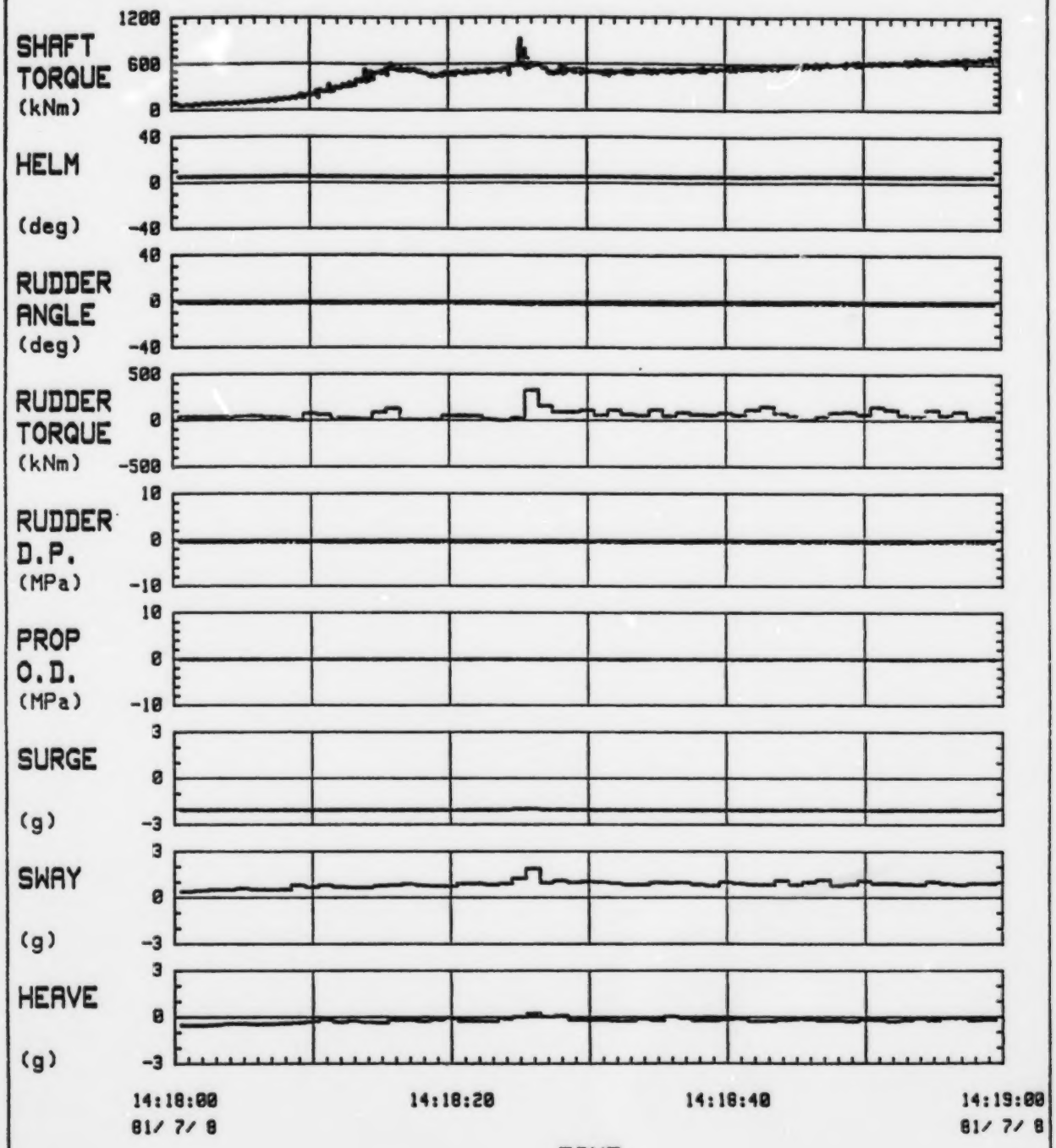

FIG. 4 SAMPLE OUTPUT FROM THE SECOND TAPE SCAN

The playback program converts the digitized record of each sensor signal output into engineering units using a set of conversion equations.

The data file generated by the playback program is transferred to the MSL in-house HP 9816 desk-top computer using an asynchronous terminal emulator program available from Hewlett Packard Co. This program enables the HP 9816 computer to emulate the input/output features of the CDC mainframe and to function effectively in transferring ASCII data files to and from the remote computer through a modem and communication system. The data, after being transferred to the HP computer, is stored on the computer's floppy disk for subsequent analysis.

A series of computer programs has been developed with the HP computer to manipulate and analyze the data transferred from the M.V. ARCTIC raw data tapes. The main functions of these programs are:

1) To identify the ice/propeller interaction events by examination of the variation of the recorded shaft thrust and torque excursion.
2) To create a data base of ice/propeller interaction event with detailed information of the ship and environment conditions.
3) To perform statistical analysis for various data categories.

The program package also has the capability to produce hard copy of the original or reduced data in tabulated or graphical form.

The created data base contains the following information for each ice/propeller event identified:

- date and time
- ship location
- transit mode
- channel condition
- peak and mean shaft torque
- peak and mean shaft thrust
- mean shaft horsepower
- mean shaft r.p.m.
- mean ship speed
- thickness and concentration of first-year ice
- thickness and concentration of old ice
- ice ridging condition
- data category
- data storage identification (tape/file I.D., etc.)

Analysis of the data was by categories based upon the type of ice and operation. The categories used are as follows:

. continuous icebreaking, level homogeneous ice
. continuous icebreaking, uniform mixed ice
. broken channel
. ramming level ice
. ramming ridges

No incidence of propeller or propulsion system ice interaction was found in the category "continuous icebreaking, level homogeneous ice". There are two reasons for this:

1) Transit of level homogeneous ice of significant thickness in commercial operation only occurs during the first voyage of the year through Admiralty Inlet when the ice is too thick to permit continuous icebreaking.

2) The data which has been recorded when breaking ice continuously has not shown any incidence of significant ice ingestion. This is probably due to a combination of the thin ice in which the data was recorded and the low speed of advance of the vessel which will permit the ice broken to be released before entering the propeller disk.

While incidents of ice ingestion have been found in all other categories, the type and amplitude of the reaction of the system was similar and do not warrant separate discussion.

4.0 RESULTS AND DISCUSSION

4.1 General

To establish a bench-mark against which the various recorded data may be assessed, recordings made when operating in open water have been analyzed. The open water signature of shaft torque and thrust for smooth and rough seas are shown by Figures 5 and 6.

In calm seas the shaft torque is seen to vary by approximately $\pm$ 8% of the mean value and thrust by $\pm$ 12% at propeller blade passing frequency (9.5 Hz). In rough seas the variation of torque increased to $\pm$ 11% and thrust to $\pm$ 20% of the mean value principally because of ship movement. If ship movements (the low frequency component) are ignored, the variation of shaft torque appears to be similar to that recorded in calm seas with respect to amplitude at propeller blade rate frequency. Shaft thrust, however, is significantly larger in the calm seas example and corresponds to 14% of mean thrust, the principal frequencies being 34 c.p.m. and propeller blade rate frequencies. The 34 c.p.m. component cannot be identified but it is highly improbable that this response is a natural mode of vibration of the shafting system due to the low frequency.

Variation of propeller shaft torque has been used to recognize events of propeller/ice interaction. In order to provide criteria which could be used to search the records automatically for significant ice effects, a value of 30% excursion of shaft torque relative to the mean torque at the time has been selected as the smallest significant event. The selection of 30% over-torque is not arbitrary and is based upon the percentage increase of MCR torque required by CASPPR for the design of gears for this class of vessel. The Rules of Lloyd's Register of Shipping also require that all gears fitted to diesel engines be capable of continuous operation at rated power with torsional vibrations up to $\pm$ 30% of the MCR torque of the engine.

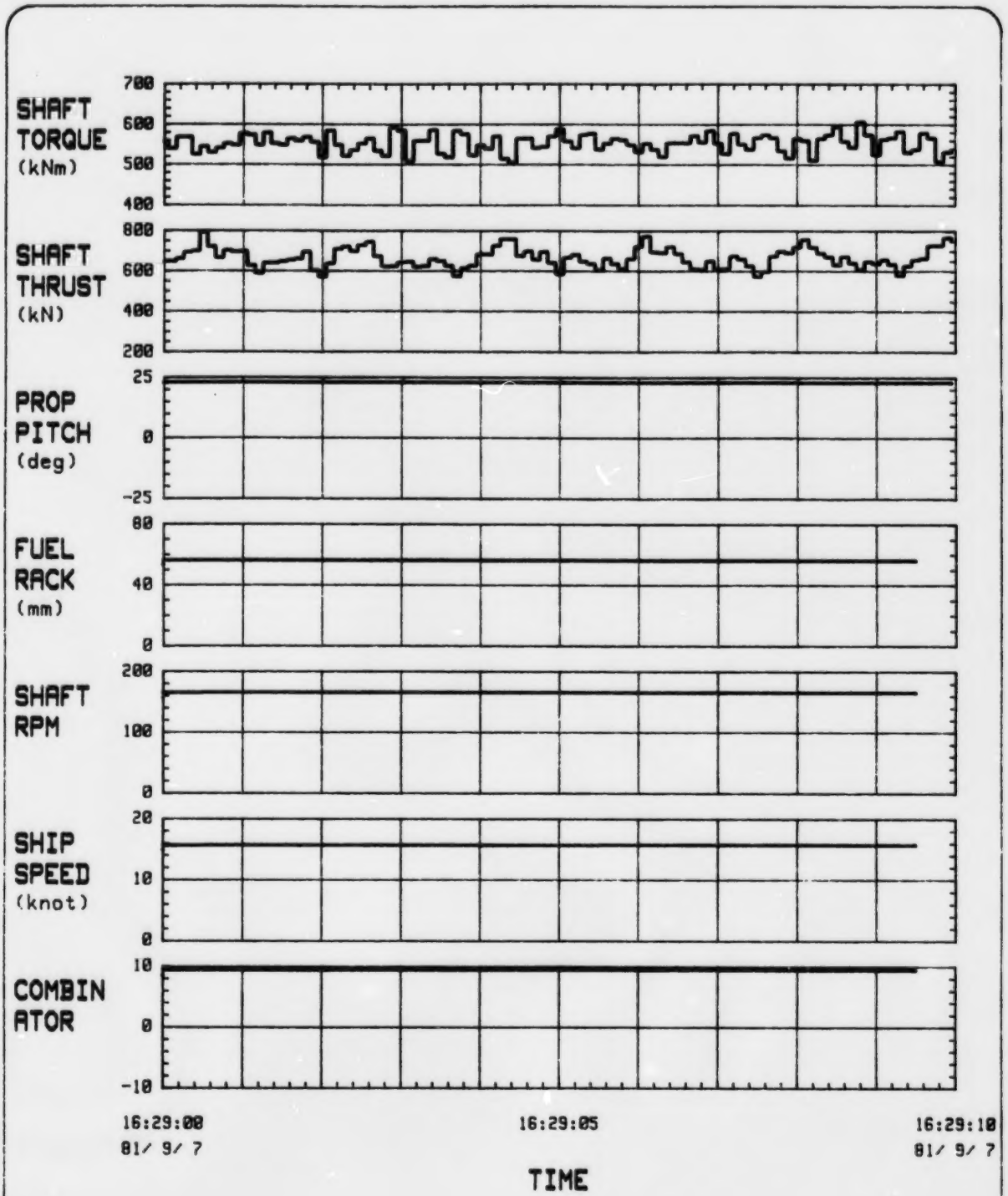

FIG. 5 PROPULSIVE PERFORMANCE RECORD

(CALM SEASTATE)

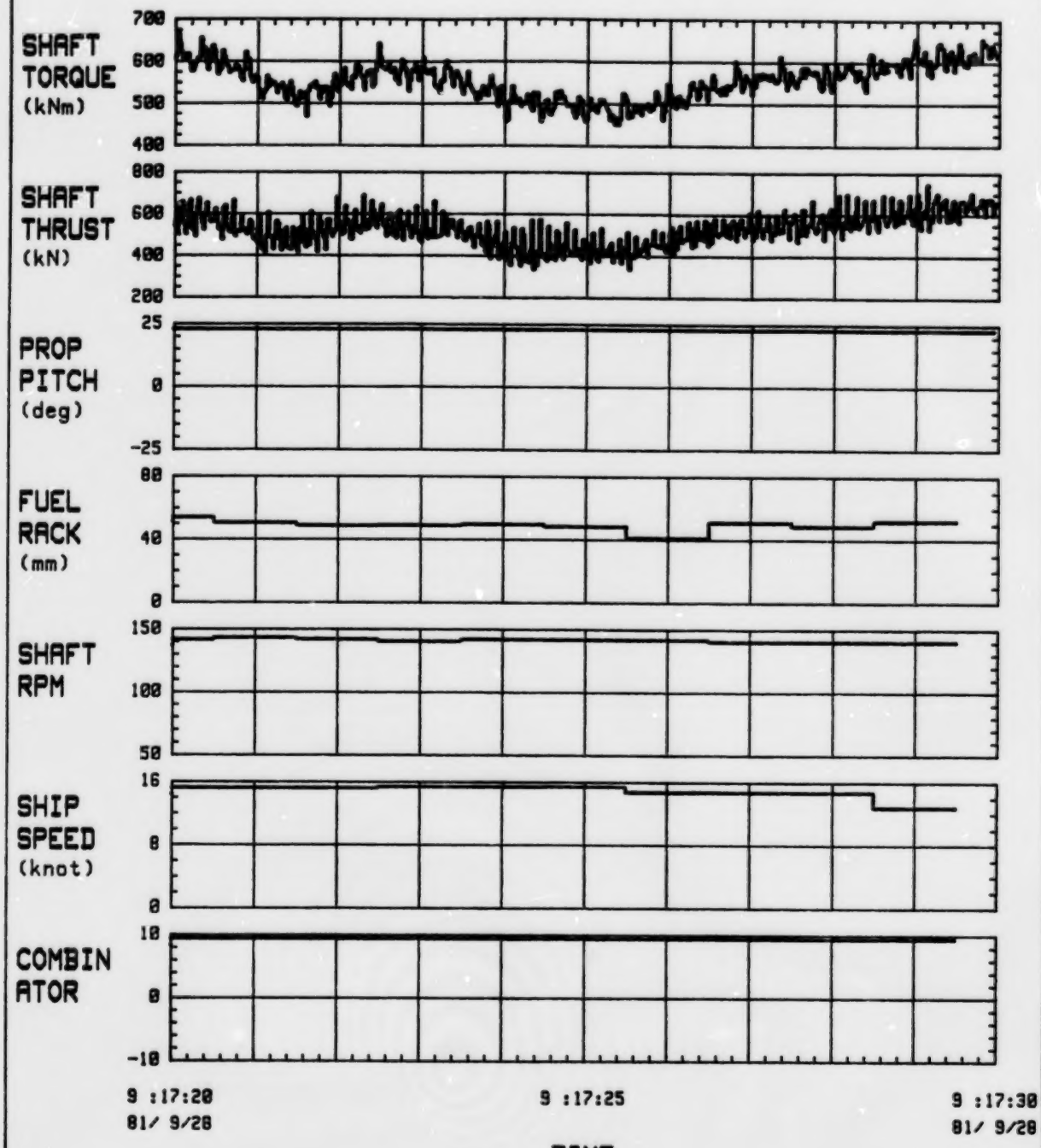

FIG. 6 PROPULSIVE PERFORMANCE RECORD

(ROUGH SEASTATE)

Ice ingestion by the propeller and the resultant impact on the blade(s) gives rise to changes of the mean and vibratory torsional, axial and bending stresses in the propeller, propeller blades and shafting system. These changes and stresses will also be transmitted to the gears. In addition, the ice will influence the wake and promote changes in the hydrodynamic forces which may excite vibrations in the shafting system. Changes in the stresses in the shafting system are transmitted to the hull through the shaft line bearings and changes in the hydrodynamic pressure by disturbances to the wake are transmitted to the hull through variations of pressure on the shell plating. Thus, ice ingestion by the propeller will also excite vibrations in the aft end structure of the vessel. The excitation forcing frequencies are invariably at the propeller blade passing frequency (9.53 Hz at rated shaft speed 143 r.p.m.) and the first harmonic. However, as the nature of the ice interaction is by impact on the blade, i.e., square or sawtooth wave form and not sinusoidal, the lowest natural frequencies of the shafting system tend to be excited.

The hydrodynamic forces acting on the hull shell plating are sinusoidal, at propeller blade rate frequency and its harmonics. As the propeller blade rate frequencies are removed from the natural frequencies of the hull girder, serious ship vibrations are not excited by ice ingestion into the propeller.

The aft end vibrations of the structure were intended to be recorded by the Data Acquisition System in terms of acceleration by three transducers positioned mutually perpendicular on the major axis of the vessel. The amplifier gains of the transducers were set to measure the vibration in terms of G (gravity) and were not sufficiently sensitive to measure the actual vibrations which did not exceed 0.1 G.

The stresses in the shafting system were measured in terms of changes in torsional strain and axial strain of the thrust block. From the measurements of torque and thrust, shear and axial stresses in the shafting were derived.

While all the data tapes of 1979 to 1981 season have been scanned, only a proportion of the data has been found suitable for analysis. All propulsion system data recorded prior to the last voyage of the 1980 season was unsuitable for analysis principally due to the incorrect setup of the shaft torque channel. As propeller shaft torque is the single and best parameter from which ice events at the propeller can be positively identified, the health of this channel is essential to the scanning of the records and subsequent analysis.

From the data of continuous icebreaking, uniform mixed ice category (total 9.6 hours of recording time), 14 events of shaft torque in excess of 30% mean torque have been shown. For the category of broken channel, 11 incidents were recognised from the records of about 10.3 hours. Forty-four events of propeller/ice interaction were found from the vessel's level ice ramming records (36.5 hours of recording time) and 34 events were found during the periods the vessel was ramming ice ridges (12.9 hours of

records). The majority of incidents of ice ingestion occurred when the vessel was stationary or operating at low speeds either ahead or astern. In general, an ice ingestion incident occurred once per hour of operation when operating in significant ice cover.

4.2 Propeller Shafting Torques

Ice ingestion by the propeller during all modes of operation took the form of one or more distinct peaks in torque followed by a succession of vibration cycles as the system returned to equilibrium. The change in thrust was similar to that of torque, see Figure 7. Detailed analysis of the records for frequency content was generally not possible due to the low sampling rates employed of 10 samples/second. Due to the low sampling rate it is possible that the peak thrusts and torques due to impact of ice with the propeller were not captured as it is estimated that the half width of the peaks are less than 0.002 second duration.

The torques generated in excess of 30% of mean torque during ice ingestion have been plotted against mean torque generated at the time of the impact. See Figure 8. While this is a convenient method to use, it should be noted that the peak torques are a function of two ratios:

- the relative inertia of the propulsion rotating system to the inertia of the ice blocks
- the strength of the propeller blade to the impact strength of the ice

It would, therefore, have been more appropriate to show peak torques as a function of propeller r.p.m., however, propeller r.p.m. was not reliably recorded.

The maximum peak torque and ice torque recorded from the data available are about 1070 and 460 kNm respectively. The peak torques shown in Figure 8 indicate that, by extrapolation, the maximum peak may reach 2 x MCR torque if the vessel is operating at full power. A peak torque of 200% MCR corresponds to approximately 48.6 MPa shear stress in the intermediate shaft and approximately 32.6 MPa in the propeller shaft, which has a larger diameter. If these stresses are compared to typical values of the yield, fatigue and design stresses for the materials of the shafting - 300 MPa, 150 MPa (pure torsion), 102 MPa (pure bending) and 60-90 MPa respectively - it may readily be noted that there are adequate factors of safety against failure.

4.3 Propeller Shaft Thrust and Reduction Gears

The analysis of the significance of variations of thrust in the shafting requires different considerations to that of torque. The shafting system dimensions are based upon transmitted torque and bending. Bending is due to the influence of the over-hung weight of the propeller, eccentric thrust and shaft alignment. In the case of M.V. ARCTIC, the axial stresses at bollard conditions due to propeller thrust are approximately 3.5 MPa and

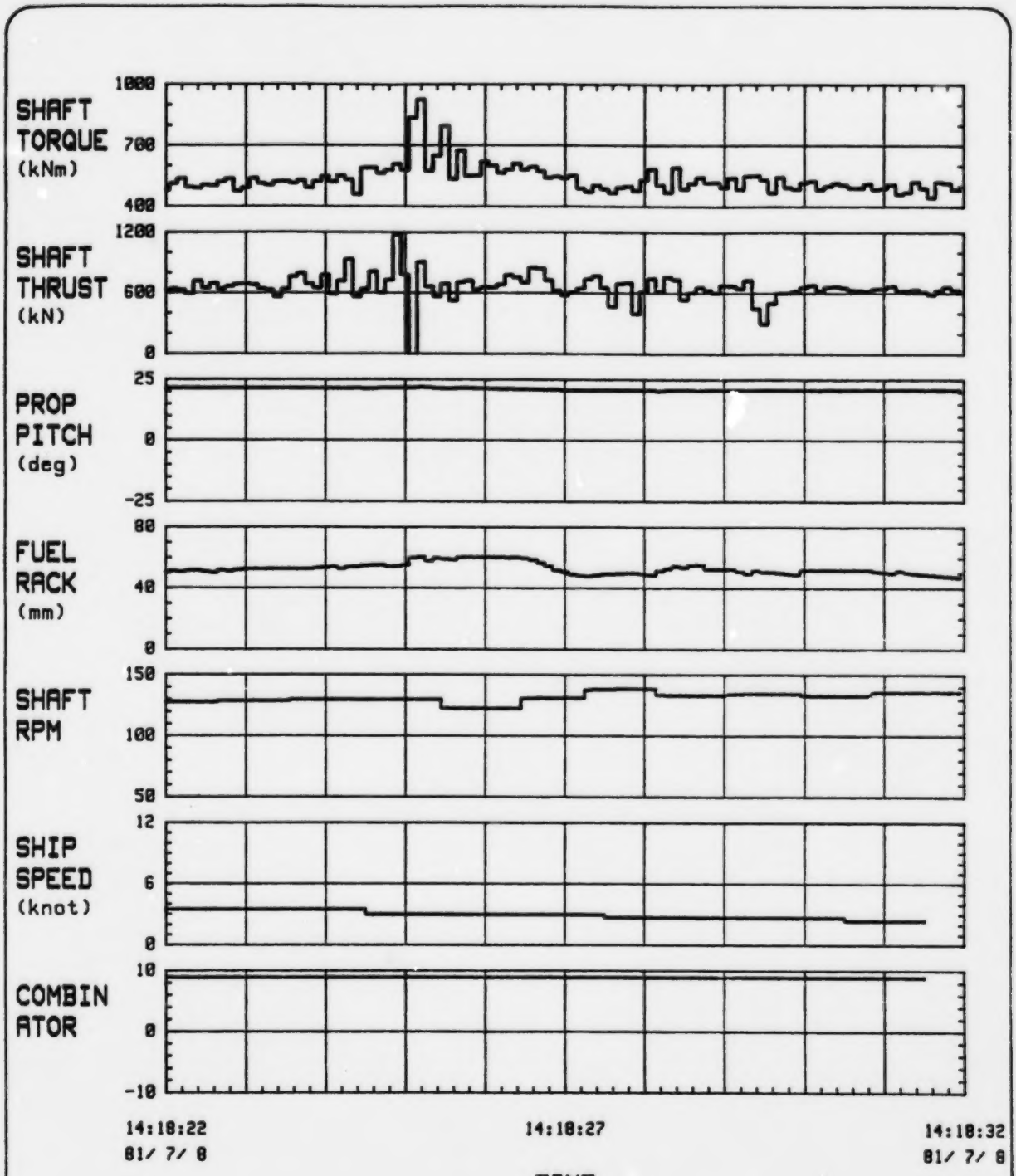

FIG. 7 PROPULSIVE PERFORMANCE RECORD

(LEVEL ICE RAMMING)

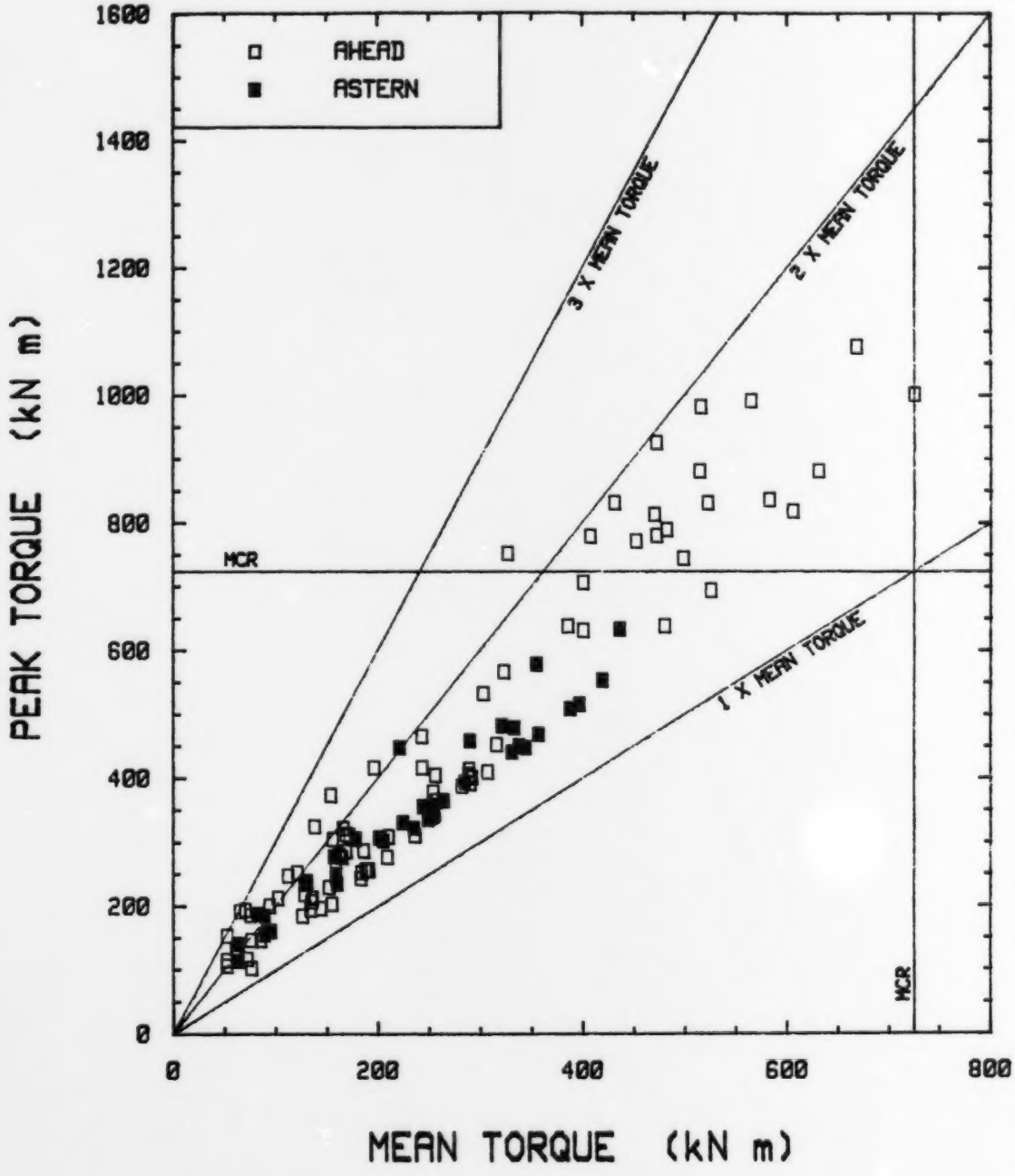

FIG. 8 ICE INDUCED SHAFT TORQUE EXCURSION

4.5 MPa for the intermediate and propeller shaft respectively, which are of no significance.

The significance of changes in thrust on the system is related to the effects of those changes upon the thrust block bearing and the gearing. As the thrust block and seating have a finite stiffness, typically not exceeding 200 tonnes/mm, and the bearing is an integral part of the gearbox, any changes of thrust will cause the thrust block assembly to deflect. This deflection may translate to changes in bullwheel to pinion alignment, see Figure 9. In addition, under certain circumstances the thrust momentarily reduces to zero, see Figure 3 and 7, or even negative, and the shaft is free to move through the thrust block clearance. If there is a sudden reapplication of load as ice clears the propeller, the thrust collar will be driven against the thrust pads. This sudden reapplication of load, in the extreme case, may cause damage to the bearings if the oil film is ruptured and structural damage to the bearing housing if the forces are extreme. The parameters recorded by the Data Acquisition System did not permit these aspects of the effects of ice ingestion to be investigated.

The initial calibration of the thrust meter limited the maximum thrust that could be recorded to 1,168 kN (1.3 MCR thrust) and caused this channel to be saturated on occasions (Figure 10). Extrapolation of the thrust records exhibits that the maximum peak thrust experienced by the vessel may reach 2 x MCR thrust when operating at full power. The peak values of thrust are not significant with respect to axial stresses of propeller and intermediate shaft.

4.4 Propeller Blade Spindle Torque

The direct effect of ice impact on the propeller was intended to be evaluated by the analysis of propeller blade spindle torques. Spindle torque was to be derived from measurements of propeller pitch changing servomotor differential oil pressure. The sensor or data channel failed to record any changes in differential oil pressure and, therefore, no analysis was possible. Spindle torque and blade bending stresses have been derived from calculations using instantaneous values of shaft thrust and torque. Due to the assumptions required to be made the calculated values of blade spindle torque and bending stress are not conclusive.

4.5 Rudder Stock Torque

The effects of ice impact or collision with the rudder on rudder stock torque was originally intended to be determined from the analysis of the recordings of rudder steering motor ram differential oil pressure. The sensor or data channel failed to record changes of oil pressure and could not therefore be used. Strain gauges were fitted to the rudder stock as temporary instrumentation to measure analogue signals of rudder shear strain by Melville Shipping Ltd. during Lake Melville Trials in 1981. These gauges were later incorporated into the Data Acquisition System. As the section modulus of the rudder stock in way of the gauges is not known, the recorded signals in ice have been interpreted relative to those recorded when turning

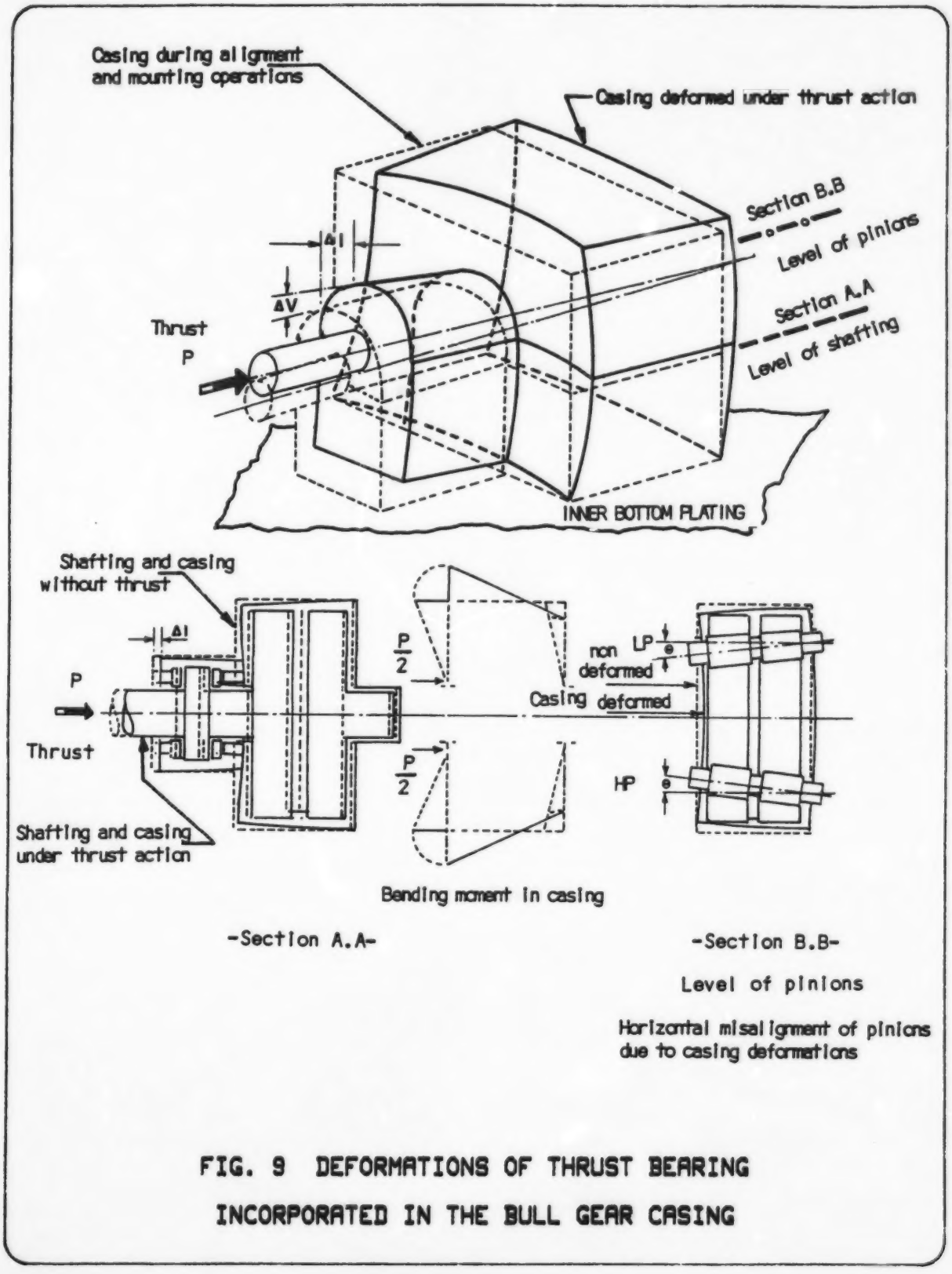

FIG. 9 DEFORMATIONS OF THRUST BEARING INCORPORATED IN THE BULL GEAR CASING

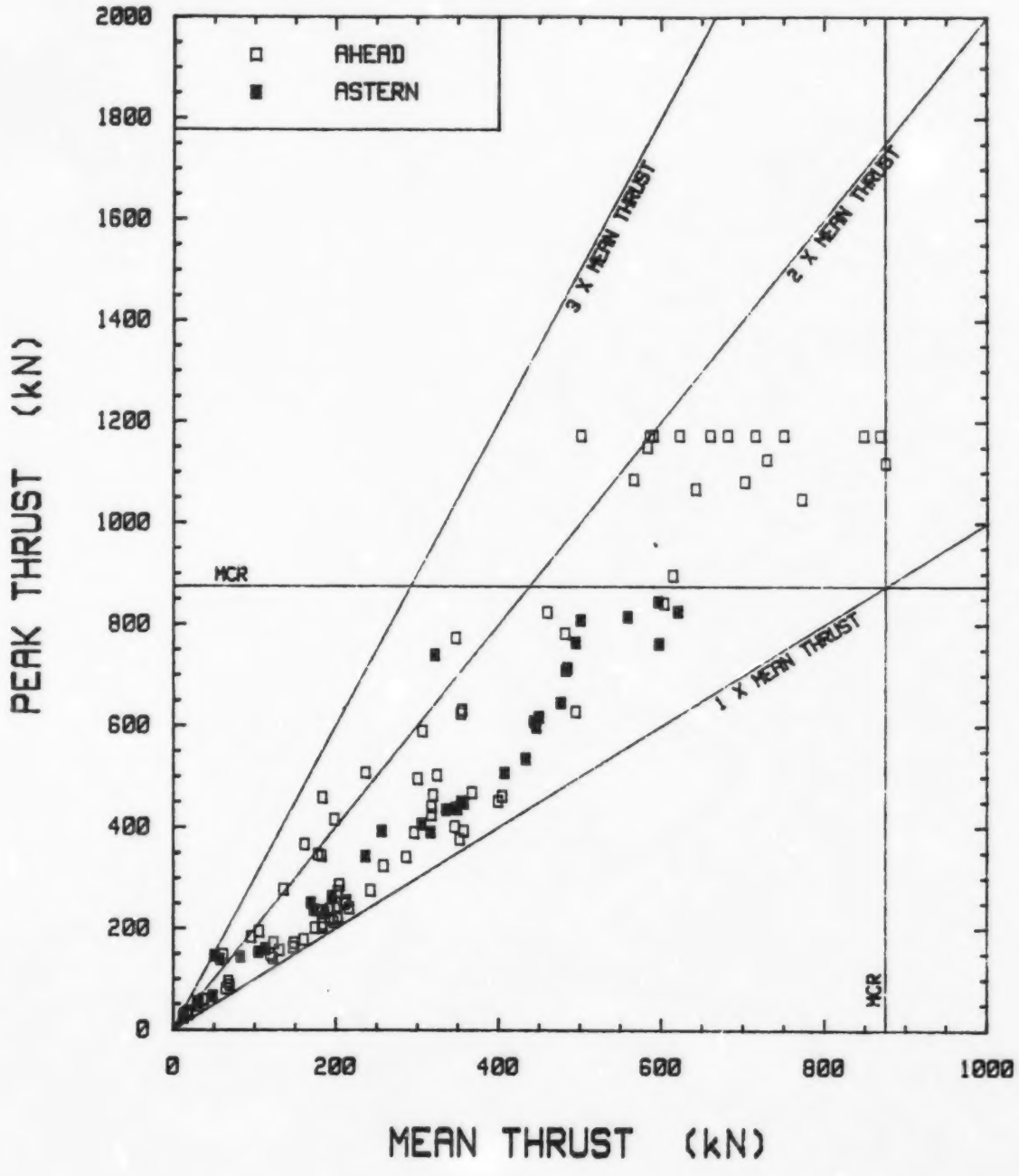

FIG. 10 ICE INDUCED SHAFT THRUST EXCURSION

in open water. The torque which had been identified due to ice impacts are all below the open water bench-marks and are not therefore believed to be of significance, see Figures 11 and 12.

4.6 Protection and Economic Advantages Offered by the Nozzle

Analysis of the recordings of shaft torque clearly show that ice ingestion into the propeller is of the form of discrete incidents of short duration. The amplitudes of these disturbances have been relatively small, not greater than 2 MCR torque and few in number. As the amplitudes of the excursions of torsional stresses are small and well below the endurance limit for the materials, there is no danger of failure of the shafting system due to fatigue.

The small stresses indicated in the shafting by propeller/ice interactions may be attributable to the nozzle which limits the size of ice pieces that can enter the propeller disk and the angle of attack of those pieces to the blades. Although these factors are undoubtedly advantageous, the M.V. ARCTIC is a large and long vessel with a fine stern and operates at approximately 11 m draft when in ice with a propeller tip submergence of approximately 5 m. Although the vessel operates in areas where multi-year ice floes thickness may be substantial, the vessel is required only to break first-year ice up to 1.8-2 m thickness. The ridges which are rammed during the first voyage of the year are generally of first-year ice, non-consolidated and comprise principally of slush below 3 m depth. It is, therefore, improbable that serious propeller/ice interaction would occur with this vessel when considering all the relevant factors:

- Ice release properties of the hull such as length, bow and stern shape
- operating draft
- ice conditions in operating area
- operating procedures
- mission profile

There are considerable technical and economical advantages given to a vessel fitted with a propeller in a nozzle compared to a similar vessel fitted with an open propeller. One of the most important characteristics of the propulsion system for an icebreaking cargo ship is high thrust at low speeds of advance when in ice while providing economical performance when in open water. This characteristic can be achieved by a controllable pitch propeller operating in a nozzle using a lower horsepower engine than that required by an equivalent open propeller.

The comparison of the economic advantages between a CP and fixed pitch propeller has been made using the existing system fitted to the M.V. ARCTIC as standard. The fixed pitch open propeller best suited to match the thrust characteristics of the fitted system at 2 knots and at the open water speed of 15 knots has been calculated to absorb 17,500 DHP, see Figure 13. If the open propeller is matched to a slow speed diesel engine which provides an advantageous fuel consumption, the difference between capital and operating

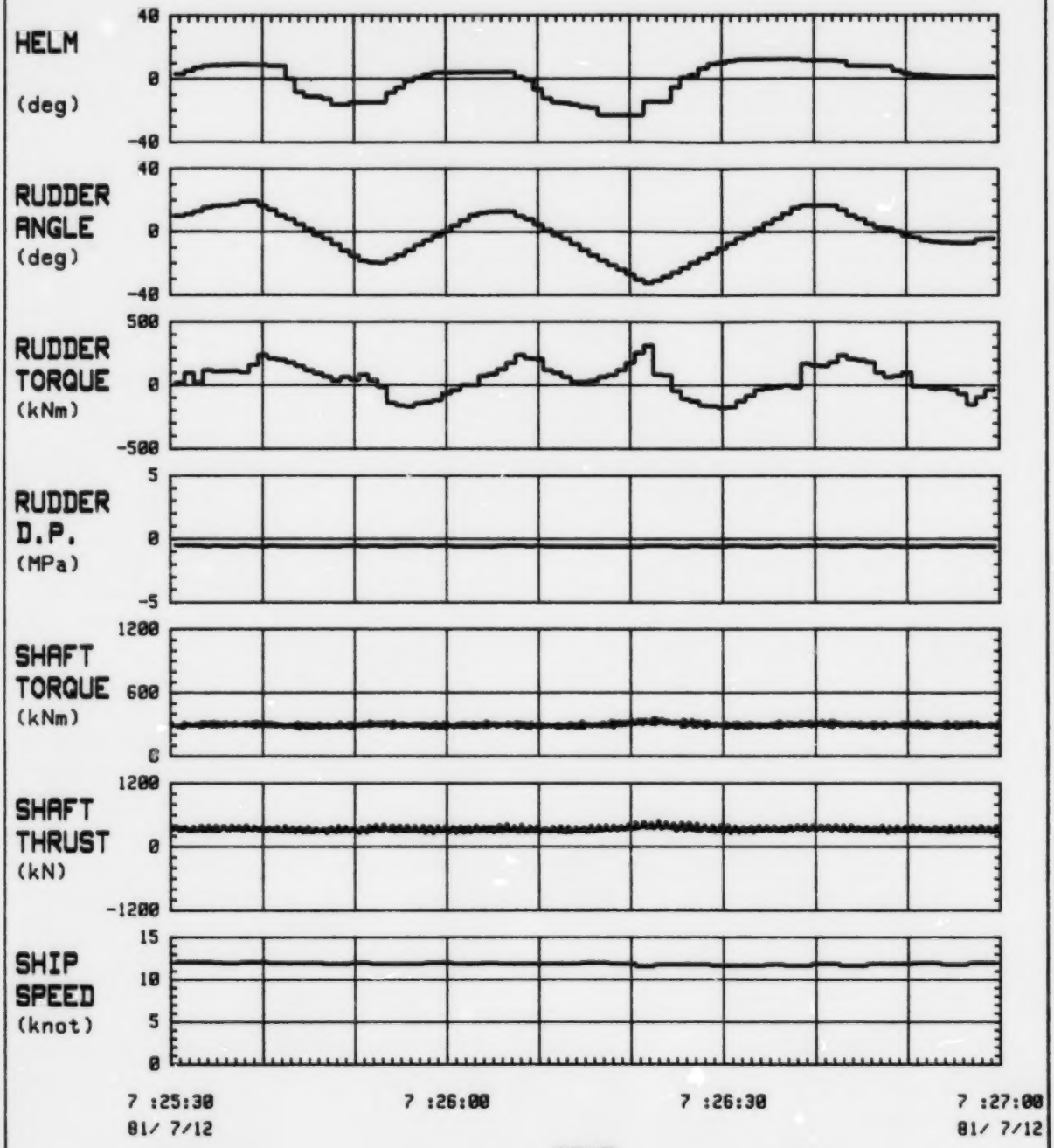

FIG. 11 RUDDER TORQUE AND RESPONSE

(OPEN WATER)

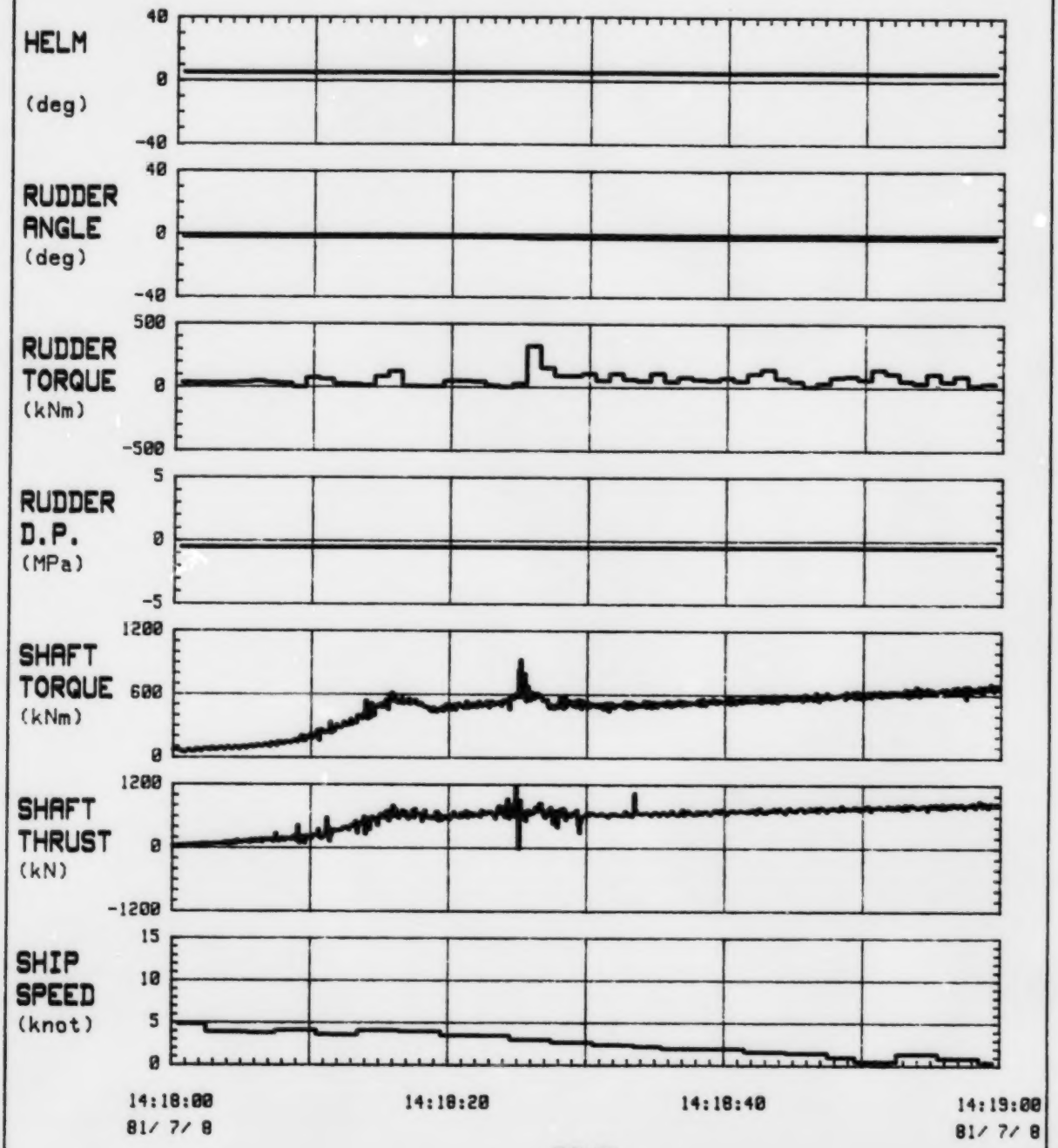

FIG. 12 RUDDER TORQUE AND RESPONSE

(LEVEL ICE RAMMING)

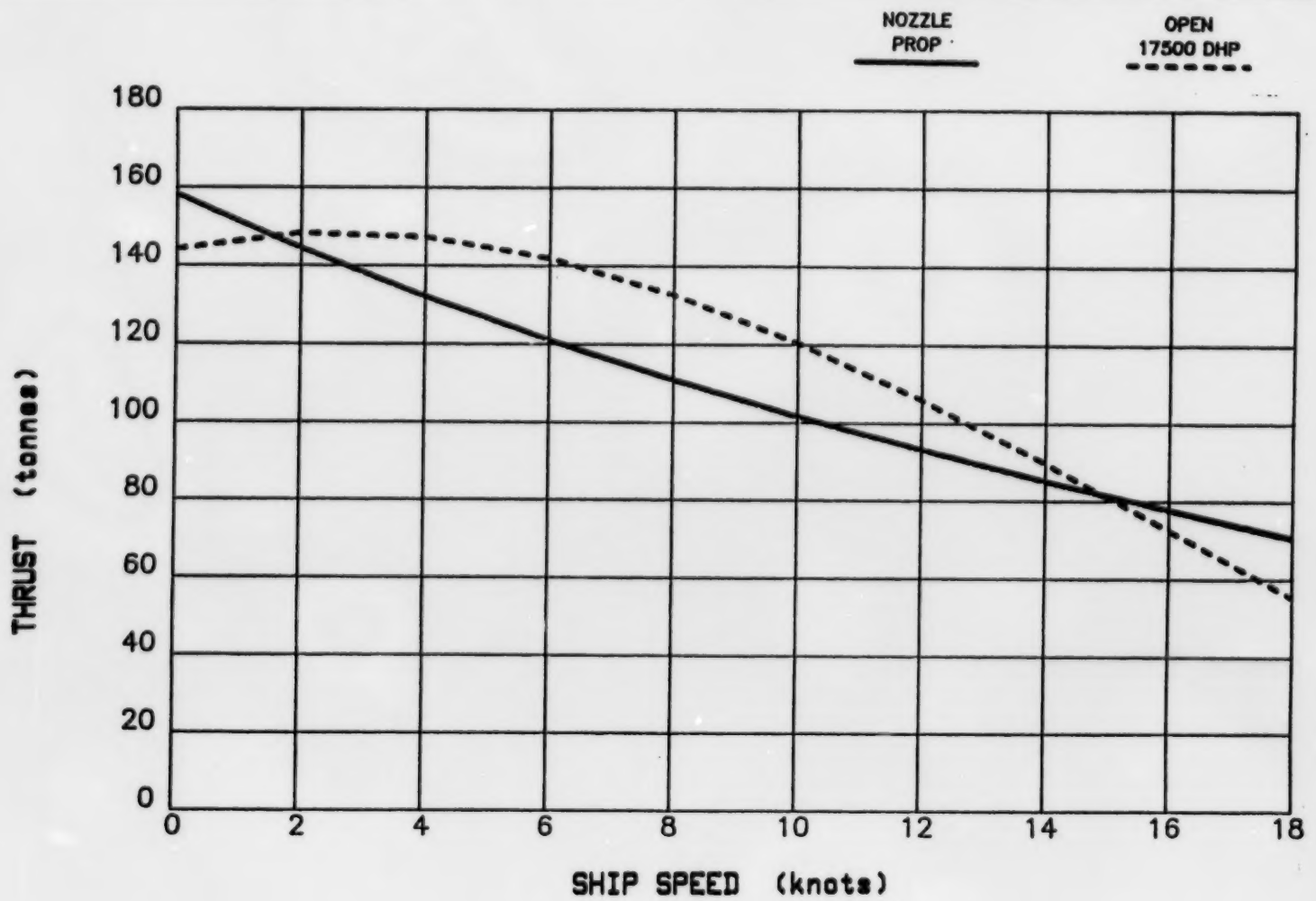

FIG. 13 PROPELLER THRUST VERSUS SHIP SPEED

costs between the fixed pitch open propeller and CP propeller in a nozzle are shown in Tables 3 and 4. From the tables, the 15 year life cycle cost, discounted to net present value, has been calculated and show an approximate $3 million advantage of the CPP system over the equivalent fixed pitch propeller system. This analysis tends to be simplistic and such factors as the ability of the slow speed engine to consume the lowest grades of fuel of the future, the effects of the cost of installation of the different systems, etc., have not been taken into consideration. To include these factors in the analysis will be difficult and subjective.

5.0 CONCLUSIONS

Within the limitations and quality of the data, there is no evidence to suggest ice ingestion by the propeller of the M.V. ARCTIC when operating normally from Europe to Nanisivik and Little Cornwallis within the period late June to mid-November gives rise to concerns of damage. The findings are based on the recorded data between 1979 and 1981 and therefore may not reflect more severe ice conditions encountered by the vessel after 1981 which may have imposed greater loads on the propulsive system.

The incidents of ice ingestion by the propeller were indicated in the excursion of shaft torque and thrust which have been measured. The majority of incidents occurred when the vessel was stationary or operating at low speeds either ahead or astern. In general, an ice ingestion incident occurred once per hour of operation when proceeding in significant ice cover, ramming ice or manoeuvring in a broken channel. No significant incidence of propeller ice interaction was found when the vessel was proceeding in thin first-year ice fields at high ship speed.

The signature of ice events revealed from the data available suggests that the propeller/ice interactions experienced by the vessel were due to ice impacts with no incidents of ice milling. Analysis of the ice event data has shown that the maximum shaft torque and thrust due to ice effects may reach 2 x MCR while the vessel is operating at full power. The effects of ice on the propulsion system took the form of discrete impacts of ice blocks with the propeller which causes instantaneous variations of propeller shaft torque and thrust. The variations have not exceeded 2 to 3 seconds duration, althougth the largest excursions of torque have on occasions caused the system to automatically reduce load (pitch) for up to 10 seconds. These events have not caused any noticable reduction in the ship's speed and have not influenced the performance of the vessel. The excursion of shaft torque and thrust and the frequency of ice ingestion incidents experienced by the M.V. ARCTIC were not of significance with respect to the torsional and axial yield and fatigue limits of the propeller and intermediate shaft.

The recorded parameters did not allow examinations of dynamic bending on the propeller shaft due to ice impact and eccentric thrust which is of vital importance to the propulsion drive train. The biggest potential for damage which has been identified is the effect on the reduction gear

EQUIPMENT	C.P. NOZZLE SYSTEM	F.P. OPEN SYSTEM	COMMENT
MAIN ENGINE			
- Slow Speed Diesel (13310 Kw)	-	4458.84	335/Kw
- Medium Speed Diesel (11014 Kw)	2533.22	-	230/Kw
GEARBOX	550.70	-	50/Kw
SHAFTING	99.13	119.79	9/Kw
PROPELLER SYSTEM			
- Fixed Pitch	-	399.3	30/Kw
- Controllable Pitch	826.05	-	75/Kw
NOZZLE	500	-	Escalated from 1975 Quote
INSTALLATION DIFFERENTIAL	250	-	Approx.
TOTAL SYSTEM	4759.1	4977.94	
		Net Difference =	218.84

TABLE 3

CAPITAL COST COMPARISON OF TWO PROPULSION SYSTEMS
(000'S 1983 U.S. $)

COST ITEM	C.P. NOZZLE SYSTEM (1) CONSUMPTION (TONNES)	C.P. NOZZLE SYSTEM (1) COST (000'S U.S.) (1983)	F.P. OPEN SYSTEM (2) CONSUMPTION (TONNES)	F.P. OPEN SYSTEM (2) COST (000'S U.S.$) (1983)	DIFFERENCE COST (000'S U.S.$) (1983)
FUEL OIL					
- 100 hrs. @ 100% MCR	229		253		
- 2400 hrs. @ 85% MCR	4673		5159		
- 3000 hrs. @ 50% MCR	3436		3793		
	8338	1668	9205	1841	+ 173
LUB OIL		87		87	-
M & R		167		172	+ 5
TOTALS		1922		2100	+ 178

(1) Consumption rate = 208 gm/Kw.hr. - Cost per tonne = 200 U.S.$
(2) Consumption rate = 190 gm/Kw.hr. - Cost per tonne = 200 U.S.$

TABLE 4

ANNUAL OPERATING COST COMPARISON OF TWO PROPULSION SYSTEMS

alignment and thrust block of momentary excursions to zero or negative thrust. The evaluation of the effect of thrust on the gears when in ice will require additional instrumentation and cannot be estimated from the parameters which have been measured. The data collected also does not provide accurate measurements of blade bending moment and spindle torque which are essential to propeller design and understanding of propeller/ice interaction.

From the limited data available there was no evidence that the rudder stock was subject to excessive torques, however, it can readily be appreciated if the vessel were to run astern into a large ice floe considerable loads would be imposed upon the rudder and stock.

The analysis which has been carried out to assess the economic advantages of the ducted propeller for this ship suggests that a CP propeller in a nozzle is superior to an open fixed pitch propeller. A saving of $3 million (Canadian) advantage in life cycle costs in favour of the C.P. in nozzle configuration is indicated. This conclusion is somewhat influenced by the assumptions which have been made and a more sophisticated approach might reveal the advantages are more significant than estimated by the methods used in this report.

6.0 Recommendations

The data which has been collected is insufficient to permit firm conclusions to be made with respect to strength of the propulsion system. More parameters require to be recorded and the quality of data collection must be of a higher standard to permit a better understanding of the loads on the propulsion system when operating in ice infested waters.

To evaluate the strength of the propulsion system, the following parameters should be measured:

PARAMETER	TYPE OF SENSOR	RECORDED VALUE	NO. OF CHANNELS
Shaft torque	Strain gauges	Shaft shear stress (transmitted power)	1
Shaft thrust	Strain gauges	Axial stress (thrust)	1
Shaft bending	Strain gauges	Bending stress	2
Gear tooth Bending	Strain gauges	Tooth bending stress	4
Rudder Stock Torque	Strain gauges	Shear stress	1
Thrust Block Vibration	Accelerometer	Displacement	1

PARAMETER	TYPE OF SENSOR	RECORDED VALUE	NO. OF CHANNELS
Sterntube Aft Bearing Vibrations	Accelerometer	Displacement	2
Rudder Angle	Potentiometer	Angle	1
Propeller Pitch	LVDT	Pitch	1
Shaft RPM	Pulse Counter	Shaft speed	1

In addition to the above, propeller blade bending and spindle torques will be extremely useful measurements but difficult and expensive to collect. The collection of propeller blade stresses would add immeasurably to the understanding of propeller/ice interaction.

The data collection should be in digital form for ease of analysis and manipulation. Most of the data can be recorded in the "peak" mode with occasional records collected in the full scan mode for frequency analysis purposes. This type of collection system will be relatively inexpensive to engineer and purchase, and will lend itself to fully automatic and unattended operation and avoid the collection of large quantities of data which is expensive and difficult to analyze.

Based upon the study of the propulsion performance of the M.V. ARCTIC, it is recommended that reconsideration of the Arctic Shipping Pollution Prevention Regulations (CASPPR) with respect to the following aspects of machinery requirements for Arctic class vessels should be undertaken.

- In the Regulations the calculation method of minimum power requirement for vessels operated in the Arctic appears to be over simplified. It is believed that the power requirement can be unambiguously defined based on continuous motion at a specific speed in level ice of a specific strength and thickness. A design ice condition should also be specified in the Regulations for a given zone and time period to provide clear guidance of power and strength requirements of the machinery of a vessel operating in Arctic waters.

- The ice torque allowance for the design of propeller blades and tail shaft, which is apparently low as compared to the torque excursion records measured from the ARCTIC, may need to be revised. The determination of design ice torque should take into consideration the dependence of propeller/ice interaction upon various types of vessels, i.e., length, draught, aft end configuration, single or multiple, open or shrouded propellers. The torque allowance should also be incorporated in the strength requirement for intermediate and thrust shaft and the reduction gear system of the vessel.

- The Regulations should address explicitly the effects of thrust loads on the machinery strength requirements. It is conceived that axial vibration and overload imposed on the propulsion drive train by propeller/ice interaction may be more significant than the torsional effects.

- The magnitude of load disturbance allowed for ice effects in the form of torsional and axial vibrations and overtorques and overthrusts should be estimated and specified in the Regulations. The load allowance should be related to the vessel types, ice conditions, the overtorque capacity of the prime mover and the inertia of the rotating system.

In addition to the above, the provisions of CASPPR should incorporate a relationship between propulsive power requirement and structural strength of the hull to ensure compatibility of the total design.